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**Final Report on Post Detection Processing and Inverse  
Problems in Ground Based Imaging**

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(Dated: November 8, 2002)

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## Abstract

This document contains the final report on the research activities supported by the AFOSR Grant No. F49620-00-1-0155 (to be called "the grant" hereafter) in the area of post processing and inverse problems in ground-based imaging over the two-year duration of the grant. The principal objective of the grant was to establish an active research program in astronomical imaging and image processing at the Maui High Performance Computing Center (MHPCC). A number of vehicles were proposed to accomplish this objective over the grant period, specifically (i) two workshops a year at MHPCC; (ii) active participation of several distinguished imaging scientists from around the country in those workshops and by collaborative visits to MHPCC and the Univ. of New Mexico (UNM); and (iii) a series of seminars and courses to stimulate, foster, and organize existing resources and research personnel working with Air Force imaging assets particularly on Maui but also at the Starfire Optical Range (SOR), Kirtland AFB. The many tangible accomplishments of this project include:

- 14 peer-reviewed journal publications, either published or under review;
- 13 conference proceedings papers;
- 30 invited presentations at workshops, symposia, universities, and conferences;
- a number of distinguished external faculty collaborators who participate in our ongoing research activities on Maui, presently funded by a five-year AFOSR PRET grant; and

- the establishment of a UNM Category I research center on Maui, namely the Maui Scientific Research Center, under the leadership of UNM Prof. Stuart Jefferies. He was originally hired to be our resident Maui research scientist to anchor the research tasks of the grant from Maui.

Based on these accomplishments, this project can be regarded as having more or less succeeded in meeting all of the objectives laid out in the original proposal. Details of the grant activities and accomplishments follow.

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## **I. INTRODUCTION, BACKGROUND, AND CHRONOLOGY OF GRANT SUPPORTED ACTIVITIES**

At the 1999 AMOS conference, both AFRL/DE and AFOSR expressed strong support for a joint vision of an active imaging research program at MHPCC that would benefit the ongoing observational and computational activities as well as emergent challenges of the AF Maui Optical Site (AMOS). The involvement of academic personnel and experts in the field of astronomical imaging and image processing was seen as a key to achieve this vision. It is in that context that the UNM Imaging Research team, led by Profs. S. Prasad (PI) and D. Tyler (co-PI), was invited to submit a proposal that was then reviewed and approved for funding under the grant.

The grant effort, with cost sharing by UNM's High Performance Computing Education and Research Center (HPCERC), had three broad objectives:

- To establish a resident research program in ground-based astronomical and space-surveillance imaging at MHPCC;
- To serve as a focal point for enhanced research collaboration between UNM/HPCERC/MHPCC and the Maui Space Surveillance Site (MSSS); and
- To increase awareness in the research community of the unique and powerful computing resources at MHPCC.

An important element of the proposed work was the organization of a series of workshops and seminars at MHPCC with the specific purpose of identifying viable

research goals in inverse problems in ground-based imaging that could be of value to MHPCC based researchers. The first workshop of the effort was held March 7 and 8, 2000 at MHPCC. A series of seminars in the area of ground-based imaging followed in the month of June 2000. A second workshop was held at MHPCC in December 2000 to explore how well the three objectives listed above were being met and to foster further collaboration between the grant investigators and external participants that included Math and Computer Science Professors R. Plemmons and T. Torgersen from Wake Forest U., Math Professor Curt Vogel from Montana State U., Prof. Doug Currie from the U. of Maryland, Dr. B. Ellerbroek from the Gemini 8-m telescope AO program, and Dr. D. Gerwe from Boeing research. The third workshop in the series, held in July 2001 at UNM-HPCC, was devoted to generate active interest among the AFRL/DE imaging research scientists at SOR in our grant activities. This was partially successful insofar as 5-7 scientists from AFRL/DE presented and attended lectures at the workshop. Those participants included Drs. J. Barchers, W. Brown, V. Gamiz, G. Loos, and M. Gruneisen. The final workshop under the grant was held at MHPCC in January 2002, and was concurrent with the inaugural PRET workshop. Each of these workshops drew nearly 25-30 participants.

A number of scientists involved in these grant activities routinely reported on their research results, attributed to the grant funding support, at important national and international conferences. Noteworthy among these conferences are the AMOS conference, OSA's Integrated Computational Imaging Systems (ICIS) conference, Annual SPIE Conference, IEEE International Symposium on Biomedical Imaging,

SPIE's Astronomical Telescopes and Instrumentation meeting, several SIAM conferences throughout the US, and several international conferences in imaging, image processing, and computational mathematics and optimization (conference names and locations can be found later in the report under "Invited Presentations").

## **II. DESCRIPTION OF RESEARCH ACCOMPLISHMENTS SUPPORTED BY THE GRANT**

Apart from the organizational objectives of the grant effort, a vibrant and productive research program leading to important publications was clearly a much sought-out end goal of the project. This end goal was more than met, as a quick glance at the long list of publications resulting from the effort easily indicates. What is attempted below is a short description of the various research accomplishments; more details can be found in the actual publications.

The first two subsections describe the work led by Professor S. Prasad, the PI.

### **A. Statistical Information Theory and Applications to Imaging**

One of the areas of research we pursued is the use of statistical information theory to characterize image formation, detection, and processing. Building upon the work of the PI on information capacity of ground based imaging systems that are beset by atmospheric turbulence (Opt. Commun. 177, pp. 119-134 (2000)), we have demonstrated [see refereed publication 12] that statistical information can serve as a



useful basis for assessing the performance of iterative image processing algorithms. It can provide, in particular, alternative, powerful criteria for stopping such algorithms from over-convergence without the need for a regularizer. One merely need monitor the mutual information, which is information successfully restored in the image plane, from iteration to iteration and stop the iterations when the mutual information is maximized. The maximization is a result of a delicate but rather poorly understood trade-off between improving resolution and amplifying noise from one iteration to the next. A considerable advantage of our approach is that it is rather naturally adapted to the particular class or classes of objects and imaging tasks of interest. By monitoring information at the individual spatial frequency pixels, or at bands of them, one can gain a deeper understanding of how such iterative algorithms process information at different spatial frequencies. This also provides a convenient way of comparing different iterative and noniterative algorithms on the same image data sets. Finally, we can in this approach reconstruct images synthetically from information-optimized spectral data that occur, in general, at different iteration numbers. Information theory has also been used to study the efficacy of prior knowledge, e.g. knowledge that objects have finite support, in pre-processing image data in order to improve their quality. Previous work by both the Co-PI and the PI (J. Opt. Soc. Am. A 16, 1769-1778 (1999)) had used noise reduction as the metric to assess the value of such prior knowledge to improve data quality. The connection of noise reduction on the one hand and information gain on the other from the use of such knowledge is not well understood, although we have devoted

some attention to it in our sponsored work.

## **B. Fisher Information and Applications to Imaging**

Fisher information has long been regarded as a very useful tool in statistical estimation theory. We have studied it both to understand it at a deeper level than before and to see how it can be employed to quantify the degree of super-resolution that is commonplace when iterative nonlinear algorithms process low-pass band-limited image data. We find that the probability distribution underlying the data from which normally a parameter is estimated can itself be estimated in terms of its cumulants. The estimation of such cumulants [see refereed publication 13] is described by a FI matrix that can be regarded as representing the ability of the data to yield the underlying statistical distribution itself. This work greatly extends the concept of the FI of a probability density function, and thus greatly clarifies the nature and meaning of this concept. Present work is being devoted to the fidelity of estimation of the derivatives of the object spectrum to increasingly higher orders from image data corrupted by a variety of noise sources, including shot noise, additive detection noise, and atmospheric turbulence. The limits on the estimation of progressively higher orders of the derivatives of an analytic function directly control the fidelity of analytically continuing the function beyond its measured values and thus the maximum ability of a reconstruction to restore spatial frequencies in an object lying beyond the frequencies contained in its band-limited image data. Encouraging preliminary

results have already been obtained.

The next three subsections describe the work led by our sub-contractor, Professor R. Plemmons, whose mathematical expertise in the theory and practice of nonlinear optimization was invaluable for the project. On a couple of the papers, he was assisted by his colleague Prof. Todd Torgersen who was also supported in part by travel funds of the grant.

### **C. Restoration and Related Topics in Image Processing**

In the paper, "Regularization methods for image restoration based on autocorrelation functions", a new approach obtained by minimizing the autocorrelation function of residuals is proposed, and various nonlinear optimization methods are compared for minimizing the associated metric, including the limited memory BFGS algorithm, which turns out to be most effective for this problem. Furthermore, a comprehensive procedure using a modified version of the Mumford-Shaw model, often used in image segmentation by variational methods, is investigated and it provides further improvement in image quality. The primary model for this study involves a nonlinear least squares approach to metric minimization. A more comprehensive approach, in a sense related to "almost" blind image restoration, is considered in the paper "A new approach to constrained total least squares image restoration". Here, errors in the blurring operator, as well as noise, are incorporated into the mathematical model. Neumann type boundary conditions, such as those often arising in the solution of

partial differential equations, are used to reduce the boundary artifacts in an effective way. More recently, in the manuscript "Iterative restoration of wave front coded imagery for focus invariance" the particular application of restoring an intermediate image resulting from encoding the phase to extend the depth of focus is considered. The primary purpose of this work is to study how well nonlinear iterative methods perform when compared to direct filtering methods for this application. In tests on real DoD data, we found that the nonlinear methods perform better, but at the cost of increased computational cost. There is a place for both approaches for this application. If real-time restoration is required, the direct filtering methods should be used. Otherwise, the nonlinear iterative methods are recommended. This study is the first of its kind for wave front coding methods in imaging.

The paper entitled "Exploiting Toeplitz structure in atmospheric image restoration" laid the foundation for later work on practical considerations in restorations using phase diverse data. This paper examines the issues of choice of cost functional and also issues of limited memory optimization. The software developed for simulation testing in this paper has been adapted for processing real telescope data.

#### **D. Deconvolution Methods in Medical Imaging**

Because of the commonality of the basic mathematical problem across imaging disciplines, our work has applications that reach beyond the domain of ground based astronomical and satellite imaging in which the original proposal was centered. Two

particular applications to medical imaging technology were considered, 3D tomography and ultrasonic medium responses. There are special concerns in using reconstructing tomosynthetic images. Such images are collected by projection methods that lie between simple x-ray radiographs, and much more expensive computed tomography techniques. In our work "Regularized, in toto, 3D restoration of of tomosynthetic images", we develop techniques for solving ill-posed large-scale problems of recovering a 3D image from a non-specific orientation of projection views by use of iterative deconvolution. This work is being transitioned to a start-up biomedical engineering company. Novel deconvolution methods are also considered in the paper "Estimation of complex ultrasonic medium responses by deconvolution". Here, the difficulty arises not so much because of the data array sizes but because the deconvolution involves complex-valued data. We incorporate the phase of the ultrasound carrier wave into the process, leading to complex data, in order to provide a more comprehensive and appropriate mathematical model for such problems.

#### **E. Some Difficult Numerical Linear Algebra and PDE Problems**

One of our papers in this direction, "Real-valued low rank circulant approximation", has applications in image compression, noise reduction, seismic inversion and latent semantic indexing. The last topic relates to data mining work for involving satellite databases relevant to the AMOS facility. A key feature in our paper is the use of FFT-based numerical procedures to speed up the computations. On the other

hand, the paper "Semi-conjugate direction methods for nonsymmetric systems" proposes a novel conjugate gradient type approach for large-scale nonlinear systems of algebraic equations. These systems arise, for example, in the numerical solution of elliptic partial differential equations formulated for control parameter identification problems.

The next two subsections describe the work led by Professor S. Jefferies in two areas, namely phase diversity and optical diffusion tomography. Professor Jefferies was the project's Maui based research scientist who not only anchored our program in Maui but also contributed seminally to the project's research focus and activities.

#### **F. Wave-front Sensing and Phase Diversity**

Phase diversity is a promising technique for improving the resolution of ground-based imagery, both through adaptive correction of the observed wave front and through post-processing of the recorded data. The paper entitled "Wave-front sensing with time-of-flight diversity" describes a new way to sense atmospheric wave-front distortion using pulsed laser beacons. Basically, a camera focused through the full aperture of the telescope at some nominal altitude to view Rayleigh backscattering, is used to record a "movie" of images of the backscattered light over a wide range of height. Phase diversity is naturally introduced into the recorded images as the laser pulses approach and pass through the focus of the camera. An iterative algorithm is then used to reconstruct the wave-front phase with a much larger signal-to-noise

ratio than is possible with existing techniques.

The paper entitled "Sensing wave-front amplitude and phase with phase diversity" investigates the importance of including the effects of scintillation when estimating wave-front phases using phase diverse data. It is shown that the quality of the reconstructed wave-front phases is significantly improved when the wave-front amplitudes are estimated along with the phases (traditionally it has been assumed that the effects of scintillation are negligible and the wave-front amplitudes are set to unity). Because the wave-front phase estimation is improved, there is also a significant improvement in the resolution of the restored object when using the wave-front phase estimates for image post-processing. The paper also shows that the quality of the reconstructed complex wave front degrades gracefully, rather than catastrophically, as the image sampling becomes coarser. This is an important point for the use of phase diversity as a real time wave-front sensor for adaptive optics, where it is highly likely that the images will be obtained on small format detectors.

#### **G. Optical Diffusion Tomography**

The three papers on optical diffusion tomography all describe the use of blind deconvolution techniques for addressing the problem of how to obtain a moderate resolution image of an object when it is viewed through a turbulent medium (e.g., clouds, fog, water, tissue). The main problem with this type of imagery is that it is difficult to accurately characterize the turbid medium sufficiently well to generate

a point spread function that can be used to deconvolve the blurred data (and thus increase the resolution). Blind deconvolution is a technique that can be used to estimate both the blur-free target and the system point spread function from a single recorded image. Our research shows that blind deconvolution is not only a good tool for improving the resolution of imagery viewed through a turbulent medium, it can also be used to determine the location of the target within the medium. Moreover, it does this without requiring any prior knowledge of the characteristics of the medium, or of what the blur-free target should look like: an important advance of the backpropagation algorithm that is normally used for post processing this type of imagery. The next subsection describes the work done by Professors David Tyler and Todd Torgersen under support from the grant.

#### **H. Image Restoration from Phase-Diverse Speckled Image Data**

This paper presents an analysis of practical problems and solutions associated with the "phase-diverse" speckle (PDS) imaging technique for reconstruction of high-resolution images from ground-based telescope data. The PDS method uses an ensemble of short-exposure images obtained simultaneously from multiple cameras to jointly estimate the object and the sequence of instantaneous phase distortions observed by each camera. Different known static phase aberrations are imposed on each optical channel; the known aberrations then function as constraints in the estimation problem. In this paper, Torgersen and Tyler extended a previously derived model



and present new data calibration techniques to compensate for various undesirable effects present in real-world PDS data. These effects include relative tip-tilt and image magnification changes between the diversity channels. The extended model and its associated (modified) objective functions were shown to lead to a new nonlinear optimization problem. Solution methods, software, and results using data from the MSSS 1.6-m telescope and the GEMINI camera system were discussed. The authors seek to explore opportunities for technology transfer of computer code developed for this paper towards an operational code for the 1.6m telescope.

Work in the area of phase diversity is on-going. Specifically, a study is under way to determine optimal parameter selection. In addition, the ground-work has begun for exploiting temporal correlation in the evolution of atmospheric phase. A third area of interest is to explore using wavefront-encoding aberrations other than defocus as the diversity observation. A key point of interest is to develop techniques for choosing a diversity phase in an optimal way.

### III. PEER-REVIEWED JOURNAL PUBLICATIONS

1. M. Chu, P. Pauca, R. Plemmons and X. Sun, "A mathematical framework for the linear reconstructor problem in adaptive optics", *Lin. Alg. and Applications*, 316, pp. 113-137 (2000).
2. M. Ng R. Plemmons, and S. Qiao, "Regularization of RIF Blind Image Deconvolution." *IEEE Trans. On Image Processing*, 9, pp. 1030 - 1044 (2000).

3. B. Ellerbroek, P. Pauca, R. Plemmons, and X. Sun, "Structured Matrix Representations of Two-parameter Hankel Transforms in Adaptive Optics," *Linear Algebra and Its Applications*, 316, pp. 29 - 45 (2000).
4. M. Chu, P. Pauca, R. Plemmons, and X. Sun, "A Mathematical Framework for the Linear Reconstructor Problem in Adaptive Optics," *Linear Algebra and Its Applications*, 316, pp. 89 - 105 (2000).
5. M. Ng and R. Plemmons, "A New Approach to Constrained Total Least Squares Image Restorations," *Linear Algebra and Its Applications*, 316, pp. 237 - 259 (2000).
6. W. Cochran, R. Plemmons and T. Torgersen, "Exploiting Toeplitz Structure in Atmospheric Image Restoration", *Contemporary Mathematics*, Vol. 280, pp. 177-198 (2001).
7. P. Hemler and T. Persons, and R. Plemmons, "3D Restoration of Tomosynthetic Images", preprint, 2001. Submitted to *Medical Physics*.
8. G. Golub, R. Plemmons, and J. Yuan, "Semi-Conjugate Direction Methods for Non-Symmetric Systems", preprint 2001. Submitted to *BIT*.
9. Jefferies, S. M., Schulze, K. J., Matson, C. L., Stoltenberg, K., and Hege, E. K., "Blind Deconvolution in Optical Diffusion Tomography", *Optics Express*, 10, 46-53 (2002).

10. Jefferies, S. M., Lloyd-Hart, M. and Hege, E. K., "Sensing Wave Front Amplitude and Phase using Phase Diversity", *Applied Optics*, 41, 2095-2102 (2002).
11. Lloyd-Hart, M., Jefferies, S. M., Hege, E. K., and Angel, J. R. P., "Wave Front Sensing with Time-of-flight Phase Diversity", *Optics Letters*, 26, 402-404 (2001).
12. S. Prasad, "Statistical Information Based Performance Criteria for Lucy Richardson Image Deblurring," *J. Opt. Soc. Am. A.*, **19**, 1286-1296 (2002).
13. S. Prasad and N. Menicucci, "Fisher Information with respect to Cumulants," submitted to the *IEEE Trans. Information Theory*, Sep 2002.
14. T.C. Torgersen and D.W. Tyler, "Practical considerations in restoring images from phase-diverse speckle data," *Publ. Astron. Soc. Pacific*, 114, 671-685 (2002).

#### IV. CONFERENCE PROCEEDINGS PAPERS

Many of the papers listed below represent invited presentations made by the grant investigators and their collaborators.

1. Z. Mu and R. Plemmons, "Regularization Methods for Image Restoration based on Autocorrelation Functions." *Optical Science and Technology SPIE Proc.*, 4116, pp. 111 - 121 (2000).

2. D.W. Tyler, "A wavefront sensor-driven variable-geometry pupil for ground-based aperture-synthesis imaging," in Adaptive Optical Systems Technology, P. Wizinowich, ed., Proc. SPIE 4007, p. 632 (2000)
3. J. van der Gracht, J. Nagy, P. Pauca, and R Plemmons, "Iterative Restoration of Wavefront Coded Imagery for Focus Invariance", Proc. OSA Conference on Integrated Imaging Systems, Albuquerque, NM, pp. 2-4, Nov. 2001.
4. Z. Mu, R. Plemmons, D. Herrington, and P. Santiago, "Estimation of Complex Ultrasonic Medium Responses by Deconvolution," Proceedings of 2002 IEEE International Symposium on Biomedical Imaging, pp. 1047-1050 (2002).
5. Jefferies, S. M., Schulze, K. J., Matson, C. L., Stoltenberg, K., and Hege, E. K., "Blind Deconvolution in Optical Diffusion Tomography", in AMOS 2001, eds. P. Kervin, L. Bragg and S. Ryan, Maui Economic Development Board, Kihei HI, 513-519 (2001).
6. Jefferies, S. M., Schulze, K. J., Matson, C. L., Hege, E. K., and Stoltenberg, K., "Imaging through turbid media: post processing using blind deconvolution", in Multifrequency Electronic/Photonic Devices and Systems for Dual-Use Applications, eds. A. R. Pirich, P. L. Repak, P. S. Idell, S.R. Czyzak, Proc. SPIE Vol. 4490, 282-289 (2001).
7. S. Prasad, "Information Based Optimization and Assessment of Image Processing Algorithms," Proceedings of the AMOS Technical Conference (Maui,

Hawaii, September 10-14, 2001), pp. 527-533 (2001).

8. S. Prasad, "Statistical Information Based Analysis of Lucy Richardson Image Deconvolution," Proceedings of the Signal Recovery and Synthesis (SRS) Symposium of the Optical Society of America (Albuquerque, NM, November 5-8, 2001), pp. 21-23.
9. D. Hope and S. Prasad, "Simulations of Information and Noise Dynamics in Support-Constrained Image Deconvolution," Proceedings of the Integrated and Computational Imaging Systems (ICIS) Symposium of the Optical Society of America (Albuquerque, NM, November 5-8, 2001), 82-84.
10. S. Prasad, "Information Capacity of Seeing Limited Imaging Systems," Proceedings of the Integrated and Computational Imaging Systems (ICIS) Symposium of the Optical Society of America (Albuquerque, NM, November 5-8, 2001), 85-87.
11. D. Hope and S. Prasad, "Application of Shannon Information in Image Post Processing," Proceedings of SPIE's AeroSense Visual Information Processing XI (Orlando, FL, April 2002), SPIE Vol. 4736, pp. 76-82 (2002).
12. D. Hope and S. Prasad, "An Information Theoretic Approach to Optical Interferometry," Proceedings of SPIE's Astronomical Telescopes and Instrumentation meeting (Waikoloa, HI, Aug 2002), to be published.
13. S. Prasad, P. Pauca, R. Plemmons, T. Torgersen, and J. van der Gracht,

"Integrated Optics Systems for Image Quality Control," Proceedings of the 2002 AMOS Technical Conference, Maui, HI, Sep 2002, to be published.

## **V. WEB-BASED PUBLICATIONS**

Full details of the workshops and the seminar series held under the auspices of the AFOSR grant are available at the grant web site <http://www.ahpcc.unm.edu/Research/AstronImaging/InverseProblems/> and at <http://www.ahpcc.unm.edu/Research/AstronImaging/ssa/>. The information available at these sites includes the schedule of talks as well as the presentation slides for most talks. An additional web site, <http://www.msrm.unm.edu/research.html>, provides information about the Maui Scientific Research Center and its various activities that were initiated with the help of the grant. Finally, R. Plemmons's publications, including those listed here, can be accessed at [www.wfu.edu/plemmons](http://www.wfu.edu/plemmons)

## **VI. INVITED PRESENTATIONS**

A number of invited presentations at professional meetings were made possible because of the funding support from the grant. They include

1. S. Prasad, "Statistical Information Processing by Astronomical Imaging Systems," an invited colloquium at the National Radio Astronomical Observatories (NRAO), VLA Array Operations Center, October 11, 2002.

2. S. Prasad, "Information Capacity of Astronomical Imaging Systems," invited presentation in the session MS-28 at the Society of Industrial and Applied Mathematics (SIAM)'s Meeting on Imaging Science, March 4-6, 2002.
3. S. Jefferies, "New Directions in Phase Diversity and Blind Deconvolution," at the National Optical Astronomy Observatories, Tucson, December 2001.
4. S. Jefferies, "New Directions in Phase Diversity and Blind Deconvolution," a Center for Advanced Studies seminar, University of New Mexico, Albuquerque, NM, December 3, 2001.
5. S. Prasad, "Information Capacity of Seeing Limited Imaging Systems," invited presentation at the Integrated and Computational Imaging Systems (ICIS) Symposium of the Optical Society of America, Albuquerque, NM, November 5-8, 2001.
6. S. Prasad, "Information Theory and Imaging: A "New" Tool for an Old Subject," invited noon-time seminar, Air Force Research Laboratory, Kirtland AFB, NM, October 17, 2001.
7. S. Prasad, "Information Based Assessment of Image Deconvolution Algorithms," invited Institute for Astrophysics Lunch seminar, U. New Mexico, Sep 7, 2001.
8. S. Prasad, "Information Dynamics in Image Formation, Detection, and Processing," invited colloquium, Dept. of Applied Mathematics and Computer

Science, Wake Forest University, Winston-Salem, NC, March 27, 2001.

9. S. Prasad, "Information, Complexity, Coding, and Images," an invited Physics 162 lecture, Dept. of Physics and Astronomy, U. New Mexico, September 29, 2000.
10. S. Prasad, "Information Theoretic Perspectives in Astronomical Imaging," an invited seminar given at the Albuquerque High Performance Computing Center, U. New Mexico, October 25, 2000.
11. R. Plemmons, "Inverse Problems in Atmospheric Imaging," at the SIAM Conf. on Computational Science and Engineering, Washington, DC, October, 2000.
12. R. Plemmons, "Structured Matrix Computations in Adaptive Optics," at the International Conference on Structured Matrices, Cortona, Italy, October 2000.
13. R. Plemmons, "Low Rank Circulant Approximations," Conference in Honor of Pete Stewart's 60th Birthday, College Park, MD, October 2000.
14. R. Plemmons, "Imaging Through the Atmosphere," SIAM Conference on Linear algebra and Applications, Raleigh, NC, November, 2000.
15. R. Plemmons, "Image Post Processing," AFOSR Workshop, Maui, HI, December, 2000.
16. R. Plemmons, "Inverse Problems in Atmospheric Imaging," International Workshop on Mathematics in Imaging, Hong Kong, China, December, 2000.



17. R. Plemmons, "Algorithms and Software for High Resolution Imaging," International Seminar on Mathematics of Computers, Patras, Greece, May, 2001.
18. R. Plemmons, "Comparison of Iterative Methods for Inverse Problems in Imaging," IMACS Conference on Iterative Methods, Heraklion, Crete, May, 2001.
19. R. Plemmons, "Inverse Problems in Optical Imaging," International Conference on Inverse Problems, Tuscany, Italy, June, 2001.
20. R. Plemmons, "Extended Focus Image Reconstruction," 2001 AMS-IMS-SIAM Summer Research Conference, South Hadley, MA, August, 2001.
21. R. Plemmons, "Algorithms for High Resolution Image Reconstruction," AFOSR Workshop, Albuquerque, NM, July, 2001.
22. R. Plemmons, "Numerical Linear Algebra in Imaging," SIAM Conference on Signals, Systems and Control, Boston, MA, August, 2001.
23. R. Plemmons, "Optimization Methods in Imaging," Inter. Workshop on Numerical Optimization, Curitiba, Brazil, August, 2001.
24. R. Plemmons, "Phase Estimation and Applications," NASA /DOD Workshop on New Directions in Atmospheric Imaging, Marshall Space Flight Center, AL, September, 2001.
25. R. Plemmons, "Restoring Extended Focus Imagery," National Security Agency Briefing on Personnel Identification/Verification, Ft. Meade, MD, October,

2001.

26. R. Plemmons, "Phase Estimation in Optical Imaging," DOD Conference on Applied Mathematics, Raleigh, NC, November, 2001.
27. R. Plemmons, colloquium presentations at Georgia Tech U. (Mathematics Dept), November 2000; NC State U. (ECE Dept.), April 2001; and Duke U. (Fitzpatrick Photonics Center & ECE Dept), October, 2001.
28. T. Torgersen, "Models and Algorithms for Atmospheric Image Reconstruction using Phase Diversity," at the Kamuela Optical Assoc. / Wave Front Sensing and Controls meeting, Hapuna, HI, November 13 - 17, 2000
29. T. Torgersen, "Practical Problems in Estimating Images from Phase Diverse Speckle Data," Maui High Performance Computing Center, Kihei, HI, December 4 - 8, 2000.
30. T. Torgersen, "Phase Diversity Models and Algorithms for Atmospheric Image Reconstruction," colloquium at the Department of Mathematics, Montana State University, Bozeman, MT, February 2001.

## VII. PATENTS

No patents resulted from the work accomplished under the present AFOSR grant.